A Wavefield Imaging Technique for Delamination Detection in Composite Structures

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ABSTRACT

In this study, a 1D scanning laser vibrometer and imaging techniques are utilized to detect hidden delamination in multi-layer composites. First, Lamb waves are excited by a surface-mounted piezoelectric wafer transducer and the corresponding out-of-plane velocities are measured by a scanning laser vibrometer. Second, wave field images are constructed from the scanned velocity signals, and the images are processed to highlight the interaction of Lamb waves with delamination. In particular, several image processing techniques such as Laplacian filtering are explored to accentuate the Lamb wave interactions with delamination from incident and reflected waves.

INTRODUCTION

In recent years, there has been an increasing demand for structural health monitoring (SHM) that apprises users of the integrity and safety of the structure being monitored [1]. SHM often infers the current condition of the structure based on a streamline of data collected from installed sensors. Guided waves have emerged as one of the leading options for structural health monitoring (SHM) due to its well established theories, its ability to detect small defects within a reasonably large inspection areas, and advancement in transducer technologies used for guided wave sensing and excitation, to name a few. Guided waves are specific types of elastic waves confined by the boundaries of a structure. For example, when a plate structure is excited at a high frequency, the top and bottom surfaces of the place "guide" the elastic waves along its axis, producing a specific type of guided waves called Lamb waves [2-4]. Various types of transducers can be used for the excitation and sensing of guided waves. The most commonly used ones are angled piezoelectric wedge transducers, piezoelectric wafer transducers, electromagnetic acoustic transducers, and comb transducers. Some are mainly used for sensing

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applications such as polyvinylidene fluoride (PVDF) and fiber optic sensors [5]. Although each transducer mentioned here has its own sets of strengths and weaknesses, all of them are primarily used for discrete point measurements. Therefore, a dense array of transducers is required to achieve a good spatial resolution and cover a large inspection area. A potential solution to this problem is to use scanning laser techniques for creating wave field images with a high spatial resolution. In this study, a 1D scanning laser vibrometer is used which can measure the out-of-plane velocity field across the scanned area. Further signal and image processing techniques are utilized to detect hidden delamination in multi-layer composites.

EXPERIMENT SETUP

User specified waves are generated using an arbitrary waveform generator. The excitation voltage is amplified using a power amplifier and applied to a piezoelectric transducer (made from lead zirconate titanate, better known as PZT). The excitation signal triggers data collection so that the excitation and response signals are properly synchronized. The guided waves generated by the PZT transducer are measured by a *Polytec PSV-400* scanning laser Doppler vibrometer. The 1D vibrometer used in this study measures the out-of-plane velocity across the scanned surface of the specimen using the principle of Doppler frequency-shift effect on light waves. The scanning is done by steering the laser beam to the desired location using deflection mirrors which are built into the laser head. Time averaging and a band pass filter are used to improve the signal quality. In order to create a high resolution wave field image it is important to have small measurement grid size compared to the wavelengths of the guided waves. The data processing is conducted using MATLAB®. Basically, three operations are conducted here. First, the raw time signals are passed through a wavelet or a Butterworth filter to reduce noise and examine wave propagation within a narrow frequency band [6]. Second, a video of wave propagation in the structure is constructed from the out-of-plane velocity information using the MATLAB® graphics tools. Third, the mean-square value of out-of-plane velocity at each scan point is computed at a given point of time:

$$E(x,y,t) = \frac{1}{2} \int_{\tau=0}^{t} v^2(x,y,\tau) d\tau \tag{1}$$

where *E(x,y,t)* is the mean-square value at the scan location at time *t*; *v(x,y,τ)* is the out-of-plane velocity at the same scan location at time $\tau\ (\forall \tau \leq t)$. *E* represents a (mass) normalized form of the cumulative kinetic energy which is the total amount of ultrasonic energy that has passed through a certain point until that time. Note that the kinetic energy corresponding only to the out-of-plane velocity is captured using a 1D vibrometer. The fourth and final operation involves the application of image filtering tools in order to accentuate the effects of interaction of the ultrasonic waves with delamination. And the performances of several image filters for blob or edge detection have been investigated. In particular, the derivative filters like Sobel and Laplacian were found to highlight the defect area successfully [7].

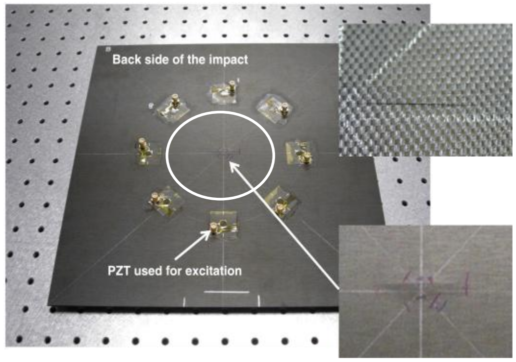


Figure 1: A multi-layer composite plate with impact-induced delamination

EXPERIMENTAL RESULTS

Delamination detection in a simple composite plate

Figure 1 shows the composite specimen tested in this study. This 275 mm × 275 mm square composite plate with a thickness of 1.8 mm. The test article was subjected to several impact tests, and the formation of internal delamination near the center.

A 5.5 cycle tone burst signal at 100 kHz was used as the input waveform. The output voltage from the arbitrary waveform generator was ±10 V and was amplified up to ±50 V using a power amplifier before being applied to the excitation PZT. One out of the eight PZT transducers installed on the backside of the impact was designated as the excitation PZT as shown in Figure 1. For each measurement point, the same excitation was repeated 20 times and the corresponding responses were averaged in the time domain.

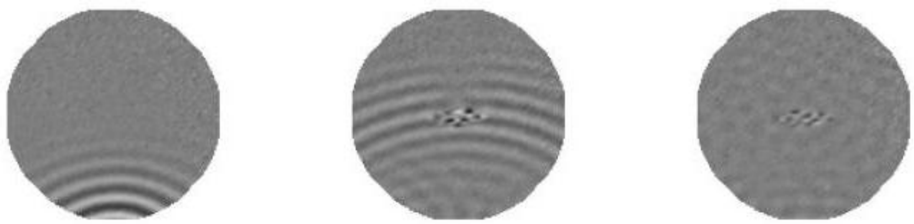
The laser vibrometer was placed about 0.8 m away from the test article, and the sensitivity of the velocity measurement was set to be 10 mm/s/V. A sampling frequency of 2.56 MHz and a band pass filer with lower and higher cutoff frequencies of 75 kHz and 125 kHz were used. The reverse side of the impact was scanned using the laser vibrometer as shown in Figure 1. The grid spacing produced a spatial resolution of 12 points/cm. This was small enough compared to the wavelength of the slowest mode (A0) in the specimen at 100 kHz. Additional scattered waves and reflections from the plate boundaries are visible in Figure 2(c). The wave interaction with the delamination becomes more prominent when the cumulative kinetic energy evolution images are created as shown in Figure 3. The figure clearly illustrates energy concentration over time near the delamination. Next, Laplacian image filtering is applied to the data shown in Figures 4 and 5, respectively.

A possible explanation for the energy concentration at the delamination location is given as follows. Hayashi and Kawashima studied guided wave propagation in a delaminated composite plate through numerical simulation using the strip element method [8-9]. I cannot remove the white space. These two paragraphs should be combined. It was observed that after entering the delamination zone, a significant portion of the incident waveform is trapped inside the zone due to multiple

reflections from the delamination boundary. If the region containing the delamination is small compared to the wavelength of the guided waves, multiple reflections would cause propagating waves from opposite directions to interfere thus producing standing waves:

$$\begin{aligned} &A\cos(\omega t - kx) + B\cos(\omega t - kx + \varphi) \\ &= B\cos(k\bar{x})\cos(\omega t + \frac{\varphi}{2}) + (A - B)\cos(\omega t - k\bar{x} + \frac{\varphi}{2}) \end{aligned} \tag{2}$$

where A and B are the amplitudes of the waves propagating in opposite directions

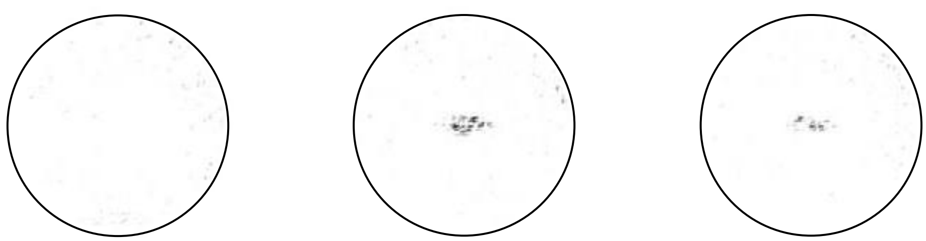


(a) 99 µs (b) 139 µs (c) 200 µs

Figure 2: Lamb wave propagation snapshots

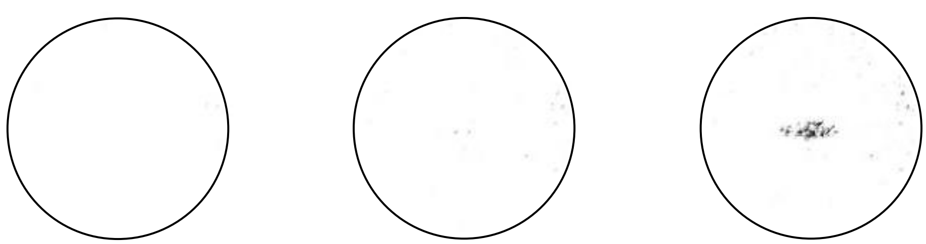
(a) 99 µs (b) 139 µs (c) 200 µs

Figure 3: Cumulative kinetic energy evolution snapshots



(a) 99 µs (b) 139 µs (c) 200 µs

Figure 4: Lamb wave propagation snapshots (with Laplacian filtering)



(a) 99 µs (b) 139 µs (c) 200 µs

Figure 5: Cumulative kinetic energy evolution snapshots (with Laplacian filtering)

due to reflections at the delamination boundary; ω and k are the frequency and wavenumber of the propagating waves; φ is an arbitrary phase; t and x represent time and space coordinates respectively where $\bar{x}$ is the zero-shifted coordinate given by $\bar{x} = x + \dfrac{\varphi}{2k}$. The first expression in the right-hand side of the equation represents the standing wave while the second one represents the part of the wave that propagates.

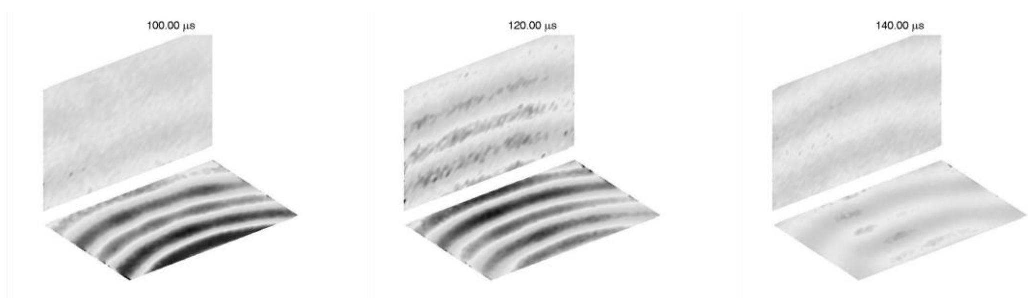
In the present study, standing waves were observed at the delamination location long after the incident propagating waves had passed that area thus corroborating the hypothesis.

Two scans in a single image

The same signal acquisition and processing techniques described earlier are now applied to an aluminum plate with stiffener. The thickness of the plate and the stiffener is 7 mm. Guided waves were generated using a PZT on the plate. The corresponding out-of-plane velocity responses in the plate and the stiffener were measured using the vibrometer. The responses in the plate and the stiffener had to be measured separately since they lie on different planes. However, the two separate wave-field images were later combined using the graphics tools in MATLAB. Figure 6 shows snapshots of wave propagation in the structure. In this way, scanned images from different parts of a structure with complex geometry can be combined to produce a single wave propagation video

CONCLUSION

This paper deals with the application of laser vibrometer imaging to detect hidden delamination in composite materials. Also it covers the application to complex specimen. Two specimens were tested for this study. One is a simple graphite-epoxy plate subjected to impact damage. The other is an aluminum plate with stiffener. Guided waves were excited in the specimens using piezoelectric transducers and a 1D scanning laser vibrometer was used to acquire the out-of-plane velocity field information across the scanned surface. Graphic tools in MATLAB® were used to create wave propagation videos as well as the videos of evolution of cumulative kinetic energy in the specimen. The delamination areas



(a) 100 μs (b) 120 μs (c) 140 μs

Figure 6: Lamb wave propagation snapshots

were found to exhibit high ultrasonic activity which was particularly noticeable in the images of cumulative kinetic energy field. Further image processing was done to accentuate the defect area with respect to the background of incident waves. In particular, the Laplacian filter was found effective in highlighting the damage area. The uniqueness of this study lies in the examination of the interaction of ultrasonic waves with hidden delamination and the application of image filters to further accentuate such interactions. The image processing technique like combining 2D scan image is found effective.

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